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An experimental test of relativistic wave-packet collapse is presented. The tested model assumes that the collapse takes place in the reference frame determined by the massive measuring detectors. Entangled photons are measured at 10 km distance within a time interval of less than 5 ps. The two apparatuses are in relative motion so that both detectors, each in its own inertial reference frame, are first to perform the measurement. The data always reproduces the quantum correlations and thus rule out a class of collapse models. This also sets a lower bound on the "speed of quantum information" to 10^7 times the speed of light.

Entanglement, one of the most important features of quantum mechanics, is at the core of the famous Einstein-Bohr philosophical debate [1] and is the principal resource for Quantum Information Processing [2]. The tension between quantum mechanics and relativity has already received quite a lot of attention in the context of local hidden variables and Bell inequality. There the idea was to complete quantum mechanics with additional variables that would reduce it to a classical theory. Here the intuition is that this tension could be a guide for new physics, beyond quantum mechanics.

Despite that there has not yet been a completely loophole free test of Bell inequality, the vast majority of physicists is convinced that quantum mechanics correctly describes the atomic world, including the correlation between distant systems, and we fully support this conclusion. Yet, after one admits the existence of non local correlation (i.e. correlation that violate Bell inequality), there come the natural questions of its compatibility with relativity and of the worldview it suggests. The answer to the first question is that there is no conflict because the quantum correlation can't be used for signaling. Hence, quantum mechanics considered as a tool to predict correlation is perfectly selfconsistent and compatible with relativity. Physicists are generally reluctant to speak about the second question, though it undoubtedly influence ones research. Some physicists would like to find a realistic interpretation of the quantum formalism, in particular to treat the state vector ψ as describing an objective reality and not merely the physicists information. We feel that such an approach is of interest, especially when it offers new experimental tests. The difficulty of realistic interpretations comes from the "wave packet collapse" (also called objectification or actualization) and there seem to be only two alternatives. The first one assumes that the collapse is only a relative phenomenon: the observer, the measuring apparatus and the quantum system under test all get correlated in a way described by the Schrödinger equation such that all future observations are consistent. In this description there is no real random choice, rather all outcomes happen in different worlds that are in quantum superposition (a so-called many-world or relative state interpretation à la Everett [3]). The second alternative assumes a real collapse with a real objective choice. It is generally believed that there is no observable difference between these alternatives. However, this conclusion depends on the exact form of the postulated collapse. For example, the GRW model [4] predicts tiny differences, though these are not measurable with todays technology.

Here we follow the idea put forward by Suarez and Scarani that a real collapse happens and takes place in the reference frame determined by the measuring apparatus [5]. This is a very natural assumption which is compatible with all previous experiments. However, when applied to EPR-like situations where moving measuring apparatuses define different reference frames [6], this assumption leads to a new tension between quantum mechanics and relativity which can be tested by original experiments.

Let us elaborate on the intuition which motivates our experiments. Each measuring apparatus defines a reference frame that we call measuring frame. In each measuring frame some measurements (performed on distant systems) happen before this one, while some happen later. The assumption is that the probabilities of outcomes are determined by the local quantum state (as in standard quantum mechanics) and that the local quantum state is collapsed by all the measurements that happened before in this measuring frame. If there is only one measuring frame, then this is identical to quantum mechanics with the projection postulate, hence the predictions are indistinguishable from those of standard quantum mechanics. However, if there are several measuring frames, then special relativity implies that the chronology of the measurements can differ from one measuring frame to another. Let us discuss the case of two entangled distant systems that for convenience we attribute to Alice and Bob. Assume first that in both measuring frames Alice's measurement takes place before Bob's. In such a case Alice produces first an outcome with probabilities determined by her local state (obtained by tracing over Bob's system). Next, Bob produces an outcome with probabilities also determined by his local state, but this state takes into account Alice's result (i.e. Bob's state is collapsed). This is quite common reasoning. Assume next that Alice and Bob are in relative motion such that in each of the two measuring frames the local measurement takes place before the distant one. In this case the probabilities of each result are determined by the local state without any collapse, hence the Suarez-Scarani model predicts that there should be no correlations at all. This is in strong opposition to the quantum mechanical predictions according to which the correlation should be observed independently of any time ordering. The case that both measurements take place after the distant one is discussed in [8].

Let us emphasize how natural the Suarez-Scarani model is in the context of assumed real collapses. Indeed, since the collapse is non local, if it is a real physical phenomenon it must happen in some privileged frame. It is then natural to assume that the latter is defined by the measuring apparatus. The attractive aspect of this idea is that it leads to difficult but feasible experiments which could severely reduce the room for "real collapse models". It also sets the question of what is an observer in a concrete context, since the observer determines the relevant measuring frame.

In order to realize a Suarez-Scarani test, we took advantage of our long-distance Bell-experiment presented earlier in more detail [9,10], see Fig. 1. A source of energy-time entangled photons is located in a Swisscom terminal in the center of Geneva. The photons are sent through the optical fiber telecom network to two villages, Bellevue and Bernex separated by 10.6 km. There, the photons are analyzed by two identically imbalanced fiber optic Michelson interferometers. The cases when the photons either both take the short arm of their interferometers, or both take the long arm, are indistinguishable leading to interference according to Feynman's criterion. One interferometer is kept at a constant temperature, while the temperature of the other one is scanned, producing a phase variation. We can thus continuously measure the correlation as a function of the phase.

According to special relativity the time ordering of the measurements differ between the two measuring frames only if their relative speed v and their time difference δt satisfy:

$$\delta t \leq \frac{Lv}{c^2} \tag{1}$$

where $L = 10.6$ km is the straight line distance between Alice and Bob. Consequently, assuming a speed v of 100 m/s and a safety margin of 2, a $\delta t \approx 5$ ps timing accuracy is necessary. This requires mastering the following difficulties:

1. determine where the collapse takes place,
2. adjust the fibers relative lengths below 1 mm (each fiber is about 10 km long),
3. master the dispersion such that the pulse spreading remains below 5 ps.

The last two items are technically challenging and will be discussed below. This first one, on the contrary, is a matter of models. Indeed, in any collapse model there is an assumed intrinsic irreversible choice after which the collapse has happened. We call the device where this happens the *choice device*.

In this letter we assume that the choice devices are the detectors. Therefore they define the measuring frames. This is a very plausible assumption, though clearly other choices are possible which would lead to other tests. In principle, in the Franson configuration that we use, there are two detectors on each side (in our case, liquid Nitrogen cooled Germanium avalanche photodiodes). We assume that on each side, one of them is in the absolute future of the other. Hence it is clearly the first one whose alignment is critical: the first detector on each side produces a random outcome whereas the second one merely confirms this choice. The two second detectors (APDs 3 & 4 on Fig. 1) show the same correlation as the first detectors (APDs 1&2). Henceforth we identify the first detectors as the *choice devices*. More precisely, we assume that the relevant physics happens in the first layers of the detectors where the irreversible absorption takes place within a fraction of a picosecond. At this point we notice that it is actually not necessary to collect the data directly from the choice devices since on each side the choices can be read from the second detector. This greatly simplifies the experiment. Finally, we argue that there is no fundamental difference between a photon absorbed by the Germanium layers of an inactivated detector and a photon absorbed by any black surface. Consequently, we replace Alice's first detector (in Bellevue) by a fast moving black surface. Admittedly, one may feel that the experimental setup (Fig 1) is too simple to test assumptions about moving observers. But there is nothing wrong in simplifying an experiment thanks to proper reasoning. The experiment sketched in Fig. 1 has the value of testing the most natural model of relativistic collapses of the Suarez-Scarani type.

To achieve a detector speed of 105m/s we use a 20 cm diameter black-painted aluminium disk of 1 cm thickness directly driven by a brushless 250W DC motor (Maxon EC) turning vertically at 10000 rpm. During the absorption, the circular motion provides a good approximation to a linear one, defining thus the inertial reference frame. It is oriented with a compass to make it run away or towards the other observer at Bernex.

We now describe the fiber lengths adjustment and dispersion management. To adjust roughly the distances from the source to the detectors we add 1.5 km of optical fiber on a spool on the link to Bellevue. Furthermore, in order to equilibrate the chromatic dispersions, we add about 500 meters of dispersion shifted fiber on the link to Bernex, this is necessary because the dispersion of this link is higher (dispersion shifted fibers have relatively high negative dispersion around 1300 nm). Finally, each fiber link measures in total about 10 km and has about 9 dB losses. Next, the fiber lengths are measured with a home made OTDR (Optical Time Domain Reflectometer) with a precision of a few cm. Short fiber pigtails are used for this adjustment. In a further step, we use another home made low coherence interferometer [11] with 100 μm resolution (using a LED with a 2 nm FWHM interference filter). Fine tuning is realized by pulling on a 2 meter long fiber on a rail with a micrometer-screw (optical fibers have 1% elasticity).

The dispersion induced spreading of the wavepackets may easily be larger than the achievable precision of the positioning. To limit the spreading we take advantage of the 2-photon chromatic dispersion cancellation phenomena [12,13]: if the central wavelength of the down-converted photons is precisely at the (average) zero chromatic dispersion wavelength of the two fibers, then, in the domain where chromatic dispersion varies linearly, both photons undergo exactly the same delay. We thus measured accurately and equilibrated the chromatic dispersion of the fiber links and found the zero chromatic dispersion wavelength with a precision of ± 0.2 nm. This uncertainty together with non-linear chromatic dispersion determines the width of the 2-photon wave-packet. Reducing the bandwidth of the downconverted photon with a 10 nm filter, we estimate that the resulting spread is below 5 ps (for a detailed analysis, see [8]).

Due to daily thermal expansion, the optical lengths between Geneva and each of the villages changes by several mm over day. We observed that Bernex is drifting further away during the daytime, since this link is more exposed to temperature variations. The drift proves to be monotonic, in one direction during the day and in the other one during the night. Accordingly, we aligned the paths taking in account the daily drift such that the optical distances from the source to the two interferometers will be perfectly equal some time later. During these few hours we continuously record the 2-photon interference fringes, scanning the phase of the Bellevue interferometer. After an acquisition we confirm with a second measurement that the path lengths really passed through the equilibrium point. In this way we are sure that some fringes are collected when the fiber lengths difference is smaller than 1 mm (corresponding to 5 ps). Many interferograms were collected over various day and night periods and measurement times. Fig. 2 displays typical data taken over 6 hours while the optical link to Bernex lengthened by 2 mm with respect to the one to Bellevue and the wheel was rotating, such that both measurements where "before the other" over almost the entire scan. Inevitably, the curves show high statistical fluctuations due to the low count rate. In spite of this, one can state that the visibility of the two photon interferogram remains constant. Especially, a reduced visibility over a scan span of 5 ps, as predicted by the model under test, should easily be noticed. After substraction of the 237±5 cts/100s accidental coincidences (which are caused by the well understood phenomenon of dark counts and which we measured independently), the fit of Fig 2 shows a constant fringe visibility of 83% [14].

We also measured interferograms corresponding to the "after-after" configuration by inversing the rotation of the wheel, again with no evidence for a breakdown of the correlations. We like to mention that with the detectors as "choice device" a breakdown of the correlations would allow to exploit "non-locality" for superluminal communication by slightly adapting the setup [8].

Our results do also demonstrate quantum correlation measurements simultaneous in the natural Geneva reference frame, setting a conservative, nevertheless impressive lower bound on the speed of any hypothetical quantum influence:

$$\frac{10.6\ km}{5\ ps} \approx 2 \cdot 10^{15}\ \frac{m}{s} = \frac{2}{3} 10^{7}\ c, \tag{2}$$

where c denotes the speed of light. We also performed this experiment without the rotating wheel and with 2 turned on and aligned detectors (APD 1 & 2 on Fig.1).

Let us emphasize again that the above bound on the speed of "quantum information" (quantum state preparation) is not in conflict with relativity. What can be said is that Alice can predict with certainty the quantum state of a photon 10 km away which was still in a completely mixed state some ps before. Whether this implies the transmission of some kind of information (or influence) is a matter of debate and models [15]. In this respect the recent progress on evaluating the cost of classical communication for the simulation of quantum correlation is interesting [16,17]: to simulate our experiment with classical communication one would not only need superluminal communication, but the extreme nonrealistic speed of 10 million time the speed of light.

We presented results of two experiments that go beyond the standard tests of Bell inequality. Their objective is to explore experimentally the possible limits of quantum mechanics, aiming at testing the most peculiar predictions of quantum physics and to open the road for further experimental investigations of these nolonger purely philosophical questions. Our results fully support the quantum predictions, re-enforcing our confidence in the possibility to base future understanding of our world and future technology on quantum principles. It also contributes to the renewed interest for experimental challenges to the interpretation of quantum mechanics. "Experimental metaphysics" questions [18] like "what about the concept of states?", "the concept of causalities?" will have to be (re)considered taking into account the results presented in this letter. For example, our results make it more difficult to view the "projection postulate" as a compact description of a real physical phenomenon [19,20,4]. However this is only a first example of this new class of tests and further experiments are needed before general conclusions can be made.

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[1] *Quantum theory and measurement*, eds J.A. Wheeler & W.H. Zurek, (Princeton Series in Physics, 1983).
[2] *Introduction to Q computation and information*, eds H.K. Lo, S. Popescu & T.P. Spiller, (World Scientific, 1998)
[3] H. Everett III, Rev. Mod. Phys. **29**, 454, 1957.
[4] G.C. Ghirardi, A. Rimini and T. Weber, Phys. Rev. D, **34**, 470 (1986).
[5] A. Suarez & V. Scarani, *Phys. Lett.A* **232**, 9, 1997.
[6] For space-like separated measurements there are always reference frames such that in the first frame one measurement happens first, while in the second frame it is the other measurement which is first, see e.g. [7]. But these frames are generally arbitrary, contrary to the Suarez-Scarani type of models where the frames are determined by natural massive devices.
[7] Y. Aharonov, & D. Z. Albert, *Phys. Rev. D* **24**, 359, 1981.
[8] Zbinden et al, full length article in preparation.
[9] W. Tittel et al. *Phys. Rev. Lett.* **81**, 3563, 1998.
[10] W. Tittel et al, Phys.Rev. A, **59** (6), 4150, 1999.
[11] N. Gisin, J.P. Pellaux & J.P. Von Der Weid, *J. Lightwave Tech.* **9**, 821, 1991.
[12] A.M. Steinberg, P. Kwiat & R.Y. Chiao, Phys. Rev. Lett. **68**, 2421, 1992.
[13] T.S. Larchurk, M.V. Teich & B.E.A. Saleh, *Phys. Rev. A* **52**, 4145-4154 (1995).
[14] This visibility is large enough for a violation of Bell's inequality. However, a violation of Bell inequality is not necessary in our context, since we do not test local models, but, on the opposite, test non-local collapse models.
[15] Ph.H. Eberhard, in *Quantum theory and pictures of reality*, ed Schommers, W., 169-216 (Springer 1989).
[16] G. Brassard, R. Cleve & A. Tapp, *Phys. Rev. Lett.* **83**, 1874, 1999.
[17] M. Steiner, quant-ph/9902014.
[18] Experimental Metaphysics, Eds Cohen, R.S., Horne, M. & Stachel, J., (Kluwer Acad. Pub., Dordrecht, 1997).
[19] Ph. Pearle, *Annals NY Acad. Sciences* **480**, 539, 1985.
[20] N. Gisin, *Helv. Phys. Acta* **62**, 363, 1989.

FIGURE CAPTIONS

1. Schematic of the experiments that consist of a photon pair source and two analyzers separated by 10.6 km, see [10]. The absorbing surface A and the rotating wheel are at equal distances from the source. In a second experiment the absorbers are replaced by two photon counters APD1 and APD2, again at exactly the same distance. We obtain typically 2 kcts/s single count rates and a mean value of about 3 coincidences per second (incl. 2 accidentals), for details, see text and [8].

2. 2-photon interference fringes measured over 6 hours, each data point corresponds to a time interval of 100s. The difference of the optical path lengths is is varying from - 8 to + 1.3 ps. Negative values mean that the detections occurs first in Bernex in the Geneva-Bernex reference frame. In the moving Bellevue reference frame the detections happen first in Bellevue over the entire scan range, as indicated on the upper time scale. Despite this different time ordering no reduced visibility is observed.